

# A Study of the Heat Treatment Effect on the Fatigue Crack Growth Behavior in Dissimilar Weld Metal Joints of SA508 Low-Carbon Steel and AISI316 Austenitic Stainless Steel

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## SA508 저탄소강과 AISI316 오스테나이트강의 이종 용접부 피로균열 성장 거동에 미치는 열처리 영향 연구

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### ABSTRACT

The effect of heat treatment on the fatigue crack growth behavior in welded joints between the heat-affected zone (HAZ) of SA 508 Cl.3 low-alloy steel and HAZ of AISI 316L stainless steel is investigated. When the crack propagates across SA 508 Cl.3 or AISI 316L SS and HAZ into the weldment, the fatigue crack growth rate (FCGR) in the HAZ region does not change or decrease despite the increase in stress intensity factor  $\Delta K$ . The residual stress at the HAZ region is more compressive than that at the base materials and weldment. The effect of the welding residual stress on the crack growth behavior is determined by performing a residual stress relief heat treatment at 650°C for 1h and subsequent furnace cooling. The FCG behavior in the HAZ region in the as-welded specimen and the residual stress relief heat-treated specimen is discussed in terms of the welding residual stress.

**Key Words** : Heat Treatment(열처리), Fatigue(피로), Crack Growth(균열성장), Dissimilar Weld(이종용접)

### 1. Introduction

A variety of parts and systems are operated in different environments in nuclear power plants (NPPs), and appropriate materials should be selected and used for such parts and systems. Thus, dissimilar welding is essential in connecting parts

made of different materials. The dissimilar welding between stainless steel pipe and a nozzle made of low alloy steel is used in a reactor pressure vessel, which is the primary system of NPPs. Plastic deformation occurs in the weld zone due to local heating and quenching during welding, and such local plastic deformation generates residual stress. In the deposited metal zone, welding defects, such as pores and non-metallic inclusions, are likely to occur. Such defects or non-metallic inclusions can

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be a starting point of fatigue cracking. Thus, the residual stress in the deposited metal zone and brittle heat-affected zone (HAZ) act as tensile stress, thereby facilitating the generation and growth of fatigue cracks, and failure accidents, such as a sudden fracture or damage due to fatigue cracks, occurring in the deposited metal zone or HAZ have been reported<sup>[1-4]</sup>. In addition, compressive residual stress reportedly causes the effect of delaying fatigue crack growth<sup>[5-7]</sup>. Thus, identifying a relationship between fatigue crack growth and weld residual stress in the HAZ of the dissimilar welding zone is an important issue in terms of maintaining structural elements and for the life extension of NPPs. However, few data are available regarding the relationship between fatigue crack growth and welding residual stress in the HAZ of the dissimilar weld zone.

This study evaluated the fatigue crack growth behavior of materials for each of the welding portions in dissimilar metals. In particular, this study investigated the comparison before and after the heat treatment of residual stress relaxation to study the effect of welding residual stress.

## 2. Experimental method

### 2.1 Test materials

For test materials, the chemical composition of the dissimilar weld zone was measured using the inductively coupled plasma mass spectrometer, as presented in Table 1. For the base metal, carbon steel SA508 and austenite steel AISI316 were used, and for the weld zone, nickel base alloy82 was

employed. To observe the microstructure of the surface by weld zone portion, an etching solution of 80ml HCl + 13ml HF + 7ml HNO<sub>3</sub> at 75 °C was used for AISI316 and the weld zone, an etching solution of 5% HNO<sub>3</sub> was used for SA508 after mechanical polishing, and an optical microscope (OM) was used to observe them. For heat treatment to relax residual stress according to the weld process, furnace cooling was conducted after maintaining the specimen for one hour at 650 °C. The samples were observed with OM using the same etching solution after heat treatment.

### 2.2 Fatigue test

The fatigue crack growth was conducted for SA508 and AISI316, including the weld zone and each material in the dissimilar weld. The stress ratio  $R(P_{min}/P_{max})$  was 0.05, and a sinusoidal wave form with 15Hz frequency at room temperature was used. The crack length was observed in real time using a mobile camera. To calculate the fatigue crack growth rate, the Paris law in Eq.(1) was used.

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

C refers to a material constant and m refers to an exponent for the independent power law of crack growth in the stress intensity factor. The stress intensity factor  $\Delta K$  was calculated using Eq. (2) for single edge notch specimen<sup>[8]</sup>.

$$\Delta K = \frac{\Delta P\sqrt{a}}{WB} \times 5\pi^{\frac{1}{2}} \times [20 - 13(\frac{a}{W}) - 7(\frac{a}{W})^2]^{\frac{1}{2}} \quad (2)$$

**Table 1 Chemical composition of dissimilar weld metals**

Materials	Elements													
	C	Si	Mn	P	S	Mo	Ni	Cr	Cu	V	Ti	Nb	N	Fe
SA508	0.002	0.35	1.58	0.032	0.001	2.47	10.82	17.41	0.43	0.06	0.001	0.02	-	Bal
AISI316	0.20	0.22	1.36	0.003	0.004	0.52	0.69	0.18	-	0.003	0.002	0.002	-	Bal
Alloy82	0.03	0.24	2.79	0.01	-	0.26	70.47	18.80	0.04	-	0.32	1.93	-	4.86

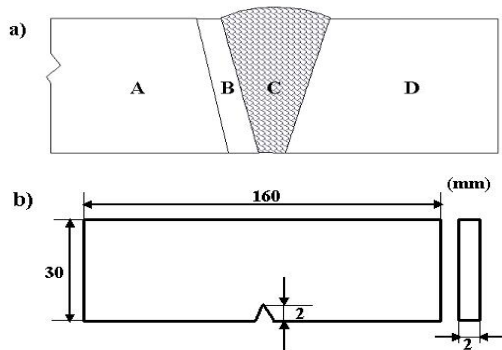


Fig. 1 Geometry and dimension of GTAW weld; (a) A: SA508, B: Buttering layer (Alloy82), C: Alloy82 weldment, D: AISI316 and (b) crack propagation specimen

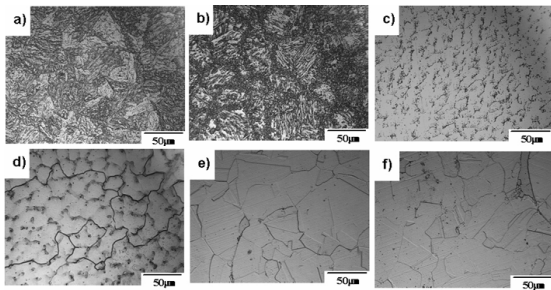


Fig. 2 Optical microstructure of as-welded specimen; (a) SA508 steel, (b) HAZ of SA508, (c) Buttering layer, (d) Weldment, (e) HAZ of AISI316 and (f) AISI316

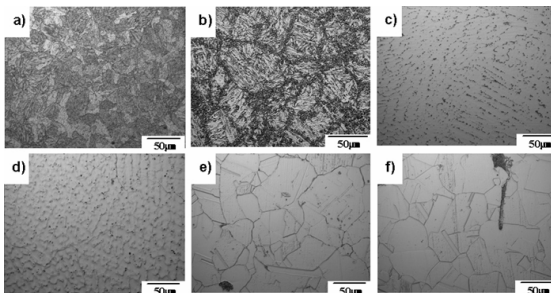


Fig. 3 Optical microstructure of heat treatment at 650°C; (a) SA508, (b) HAZ of SA508, (c) Buttering layer, (d) Weldment, (e) HAZ of AISI316 and (f) AISI316

Here,  $a$ ,  $W$ , and  $B$  refer to the crack length, specimen's width, and specimen's thickness.

The fatigue crack growth rate and stress intensity factor were created using a log-log scale via the incremental polynomial expression method<sup>[4]</sup>.

The distribution of residual stress at the dissimilar weld zone was measured using a continuous indentation test method from SA508 to AISI316 at a constant gap<sup>[9]</sup>.

### 3. Experimental results and discussion

#### 3.1 Microstructure

Fig. 2 shows the observation results of surface microstructure at each of the weld portions of the dissimilar weld zone. SA508 was an upper bainite structure where the lath was well developed. Fig. 2(a) shows the observation results. As shown in Fig. 2(b), a martensite structure was observed in the HAZ of coarse SA508 Cl. 3 steel. The single phase of austenite was observed from the microstructure in the weld zone and the buttering layer, as shown in Fig. 2(c) and (d). A typical austenite crystal grain of polygon including many annealing twins was observed at the HAZ in AISI316 and base metal AISI316. Fig. 3 shows the surface microstructure observed in the welding portion after heat treatment at 650°C. The observation results of Figs. 2 and 3 via OM showed no significant changes in the microstructure in the HAZ of the specimen of the dissimilar weld zone before and after heat treatment. This was because the heat treatment for residual stress relaxation was limited to observe the change in the surface microstructure via the OM with low resolution. The fatigue crack growth behavior in each of the materials prior to heat treatment is shown in Fig. 4(a).

The observation revealed that the fatigue growth rate of SA508 was the fastest at the same  $\Delta K$ , but when  $\Delta K$  was  $38\text{MPa}\cdot\text{m}^{-1/2}$ , the same fatigue crack

growth rate appeared, and the fatigue crack growth rate of AISI316 grew faster than that of SA508 as  $\Delta K$  increased continuously. The fatigue growth rate in the weld zone was very irregular. The experimental results showed that despite the increase in  $\Delta K$ , the fatigue crack growth rate rarely changed or decreased, and the region was observed in the heat-affected zone(HAZ). Generally, fatigue cracks grow at the crack tip due to the repetition of opening and closing cracks. If the compressive residual stress is present at the crack tip, it acts as a hindrance to the crack opening<sup>[10]</sup>.

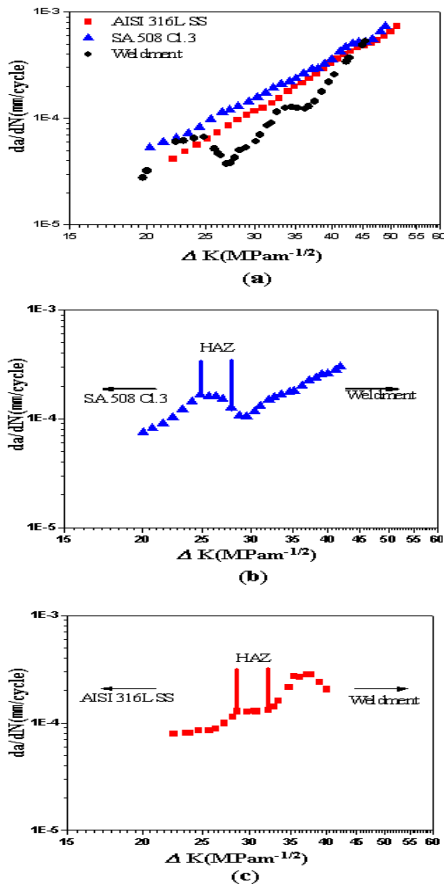


Fig. 4 FCGR in (a) and (b) SA508 to weldment; (c) AISI316 to weldment

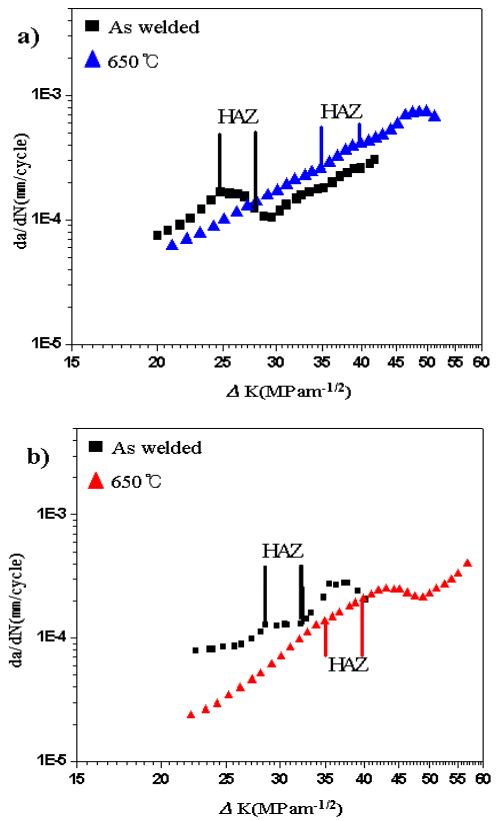
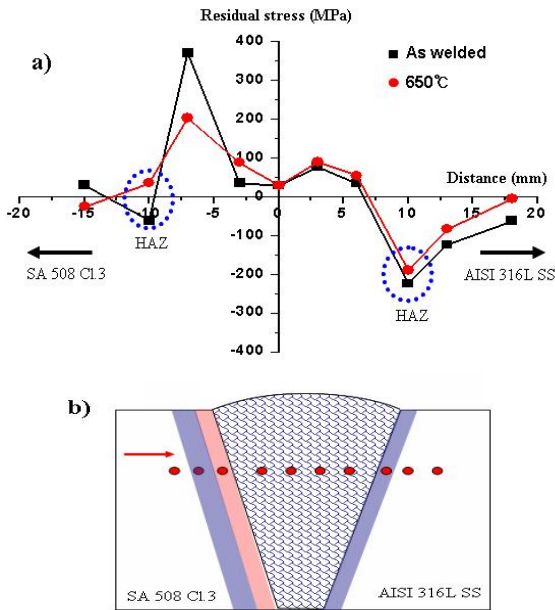


Fig. 5 FCGR in (a) SA508 to weldment and (b) AISI316 to weldment

The delay or reduction in the fatigue crack growth rate in the HAZ was due to the effect of weld residual stress that occurred during the weld. Figs. 5(a) and 5(b) show the comparison of the specimens after heat treatment on the fatigue crack growth behavior, which started from SA508 and AISI316 and penetrated the weld zone via the HAZ. The delay or reduction in the fatigue crack growth rate observed in the HAZ prior to heat treatment could not be observed in the specimen after heat treatment. Given that no significant microstructural change was exhibited before or after (refer to Figs. 2 and 3), the above phenomenon was due to the relaxation of the residual stress in the HAZ through the heat treatment.



**Fig. 6 (a) Residual stress distribution measured by the continuous indentation technique, (b) Schematic diagram of GTAW showing the points of indentation**

The residual stress distribution was measured through the continuous indentation technique.

Fig. 6(a) shows the residual stress distribution through the continuous indentation technique. The HAZ of SA508 and AISI316 prior to heat treatment showed a compressive residual stress of 61 MPa and 224 MPa. The HAZ of SA508 and AISI316 after heat treatment at 650 °C showed a tensile residual stress of 35 MPa and a compressive residual stress of 190 MPa. The residual stress in the region, including SA508 and the HAZ prior to heat treatment, was distributed in the direction of the compressive residual stress and changed to the distribution in the direction of tensile residual stress after heat treatment. The residual stress in the region of AISI316 and the HAZ was distributed in the direction of the compressive residual stress both before and after heat treatment, but the compressive

residual stress was considerably relaxed after heat treatment. Thus, no delay or reduction in the fatigue crack growth rate was observed due to the relaxation of compressive residual stress in the HAZ after heat treatment. However, the residual stress remained even after heat treatment in the HAZ of AISI316 to some extent, and the delay in the fatigue crack growth rate was not very large during observation and may require additional in-depth analysis in the future.

## 4. Conclusion

The study results on the effect of heat treatment on fatigue crack growth behavior in the dissimilar weld zone of SA508 and AISI316 can be summarized as follows.

1. The HAZ prior to heat treatment showed a delay or reduction in the fatigue crack rate, but this phenomenon was not observed after heat treatment.
2. No significant changes were found in the microstructure of the HAZ before and after heat treatment for one hour at 650°C. However, the comparison results after measuring the residual stress distribution of the specimens before and after heat treatment showed that the compressive residual stress in the HAZ after heat treatment was significantly relaxed.

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